A MICROWAVE METHOD OF MEASURING SURFACE ROUGHNESS

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1. Introduction

The electrical characteristics of microwave equipments, such as cavity resonators, transmission lines, depend a great deal on the characteristics of the walls which embody them. The currents flowing in the walls having finite conductance cause loss, the amount of which depends on the conductivity of the metal the walls are made of, and on their surface roughness.

The skin-depth of the materials used in microwave technique is very small (for example on 3000 MC/s the skin-depth in silver is 1.2 μ). The microwave loss is, therefore, determined by the uppermost layers of the walls, their thickness being a few microns at the most.

In practice the theoretical calculations assuming ideal smooth surface and homogeneous medium give somewhat lower losses, than those measured. The difference might have two reasons; first: the conductivity of the metal differs from the assumed value, second: the surface of the metal is rough. It might be theoretically proved that the specific resistance of metals increases, if the skin-depth is smaller than the so-called free path made by an electron in the metal between two collisions; or to put it in other words, if the time period of the microwave oscillation is in the same order as the time spent between two collisions of the electrons.

At normal ambient temperatures these phenomena become effective only on wavelengths of a few tenths of millimetres. More important is the fact that the specific conductivity of the test piece might differ a great deal from the ideal value assumed. There are several references in literature underlining the necessitiy of measuring the D. C. conductivity of the material under test, before the microwave measurements.

With this method, however, only the average specific conductivity of the tested material can be determined. The structure of the materials in practice is inhomogeneous, and besides this, the technological processes cause local changes in the conductivity, too. These latter, especially machining, are effective to those outer layers, in which the microwave currents flow. The surface roughness of the wall might cause a considerable increase of loss, if the value of the unevenness is comparable with the skin-depth. According to data in the literature [1], 60% increase of loss results if the scratches on the surface are perpendicular to the direction of current flow. A much smaller increase in loss results if the scratches lie parallel to the wall currents.

From these it is apparent that losses depending on the qualities of the wall can only be determined experimentally.

To find the best technological method, all the different processes must be checked by a series of experimental measurements. It would be too expensive and in many cases the checking itself might be extremely difficult to achieve, if the technological tests were done on microwave apparatus, which are very expensive and exceedingly difficult to make.

The measuring method discussed above, which can be applied for checking the series of technological experiments, makes use of cylindrical test piece, one, which is easily made. The aim of the measurement is to determine the surface roughness due to microwave losses.

In order to select the effects on microwave losses of the specific resistance and the surface roughness of the metal used, the measurements must be made on two essentially different frequencies, and the ratios of the effective specific resistances measured on microwaves and on ultra-shortwaves, resp., will correspond to the microwave surface roughness.

The first measurement is made on a frequency on which the unevenness of the surface is negligible in comparison to the skin-depth. (According to available data in literature, a surface roughness of $^1/_4$-th the skin-depth causes only 4% increase of loss at the most.)

The specific resistance measurement was made on a frequency a 100 times less than the microwave band, so that the surface roughness was negligible in respect to the skin-depth in all the practically important cases.

During these measurements the skin-depth was in the order of .01 mm, so it was possible to determine the increase of specific resistance due to the changes of metal structure caused by the different technological processes. When special precautions are used, this method is also suitable for examining electro-plated layers. The specific resistance measured by microwaves was counted from the Q factor of a resonant cavity made specially for this purpose.

2. Measuring methods

2.1. Measurement of specific resistance on very high frequencies

The measurements were made on simple cylindrical test pieces, the dimensions of which were chosen according to the microwave band used. (This method is suitable for testing non-magnetic materials only.)

The cylindrical test piece was wound around the middle by a considerably shorter coil. The gap between the test piece and the coil is filled in by a low loss dielectric (*e. g.* polystyrene), as shown on Fig. 1. Suitable bumpers secured the same positions of both test piece and coil at all measurements. The higher the Q factor of the empty coil is, the greater is the accuracy and efficiency of the measurement. If test pieces with the same dimensions but of different materials are placed into the coil in the same position, the Q factors, measured

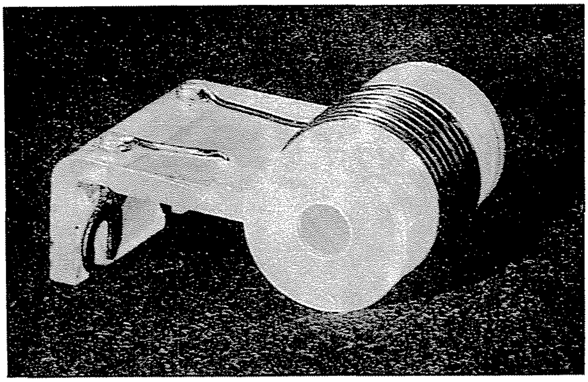


Fig. 1. R. f. measuring coil [1, 2 and 10 MC/s] into which the test piece is put and its Q factor measured by a QVH type Q-meter

at the same frequency will correspond to the specific resistances of the test pieces.

The coil losses might also be taken into account by a corrective factor, if necessary. In case a homogeneous test piece, manufactured with utmost care is used as a reference, and its specific resistance at D. C. and at high frequencies is the same, then it is possible to determine, by this measurement, the specific resistance of the uppermost layer of the test piece, the depth of which does not exceed a few hundredth of a millimetre. The Q factor had been measured by a Rhode—Schwarz type QVH-BN 3672 Q-meter on approximately 10 MC/s. The measuring arrangement is shown on Fig. 2.

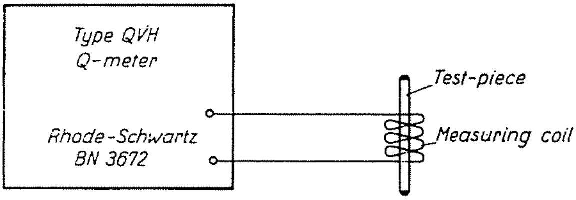
It can be theoretically shown, that if a core of infinite length and of $2\,r_0$ diameter is placed into an infinite coil of $2\,r_1$ diameter, and if the skin-depth of the core is δ, then the Q factor of the coil is determined by

$$Q = \frac{\pi\,(r_1^2 - r_0^2)}{2\pi r_0 \dfrac{\delta}{2}} \tag{1}$$

in case $\dfrac{r_0}{\delta} \gg 1$.

If the coil itself has losses, the resulting Q_r factor is given by

$$Q_r = \frac{Q_t \cdot Q}{Q_t + Q} \tag{2}$$



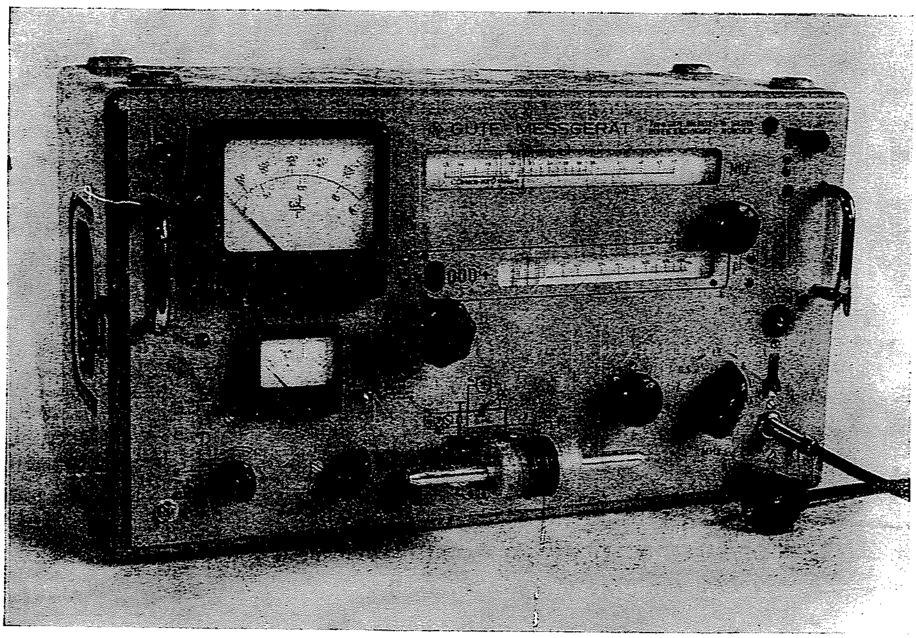


Fig. 2. Measurement of specific conductivity with a QVH type Q-meter

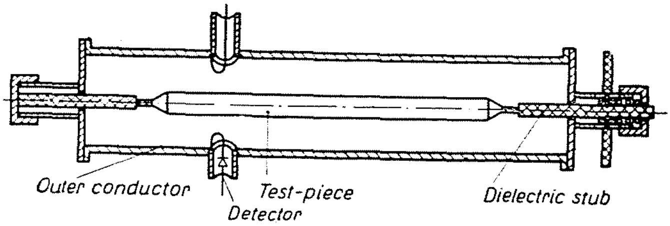
where Q_t is the Q factor of the coil, in case a core of the same diameter but made from a material with infinite conductance is placed into it. The specific conductance of the material that the core is made of can be calculated from

$$\sigma = \frac{Q^2}{r_0^2 \pi f \mu_0 \left[\left(\frac{r_1}{r_0} \right)^2 - 1 \right]^2} \tag{3}$$

where f is the frequency used, μ_0 the permeability of the air.

2.2. *Measurement of specific resistance on microwaves*

The measurement of specific resistance is now restricted to measuring the Q factor of a coaxial cavity resonator. The cylindrical test piece acts as an inner conductor in a cavity resonator using the TEM mode, as is shown on Fig. 3. The inner conductor is shorter than the cavity itself and is placed



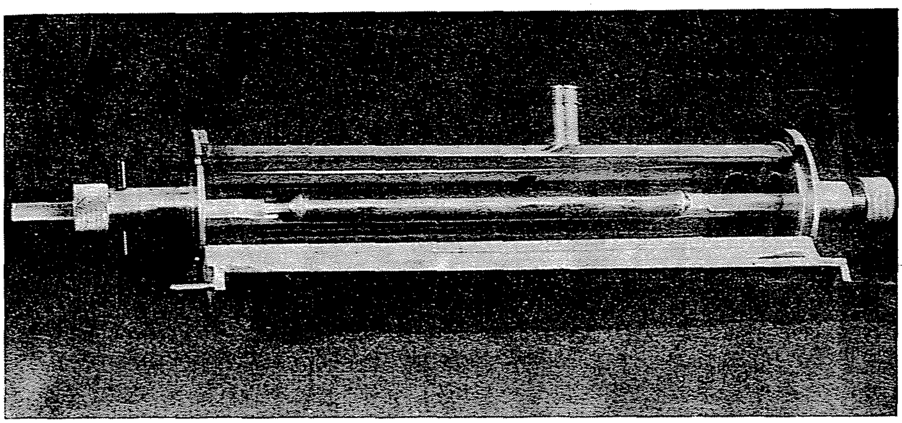


Fig. 3. Coaxial cavity resonator suitable for measuring specific conductance

in the middle. The cavity must be dimensioned in such a way, that the operating frequency band should lie below the cut-off frequency of the sections without an inner conductor. In this case these sections only cause a small capacitive load to the section having the inner conductor.

In this way there is practically a voltage maximum on both ends of the inner conductor. The length of the inner conductor is appr. an integer multiple of half of the wavelength at resonance. The true resonant wavelength is somewhat longer than the former theoretical value. A test piece of greater length might be examined at more than one frequency.

The advantage of the method discussed above lies in the fact, that there are no conduction currents between the inner and outer conductors, so all possibilities of bad or improper contacts have been eliminated. The test piece is held by conical dielectric rods concentric to the cylindrical outer conductor. One of these conical dielectric rods is fastened to its place by a screw, while the other is pressed against the inner conductor by a spring. If this latter rod is pulled back against the force of the spring, the test piece is then easily accessible and can be taken out. The outer conductor is axially slotted and this slotted section, turning around one side, can be opened or closed like a door, which makes the easy handling of the test piece possible. Having closed this slotted section the remaining gaps have no importance for they are parallel to the wall-currents.

The Q factor of the cavity is:

$$Q = \frac{2 \ln \frac{b}{a}}{\frac{\delta_1}{a} + \frac{\delta_2}{b}} \tag{4}$$

$$\frac{1}{Q} = \frac{1}{Q_1} + \frac{1}{Q_2} \tag{5}$$

$$\frac{1}{Q_1} = \frac{\frac{\delta_1}{a}}{2 \ln \frac{b}{a}} \tag{6}$$

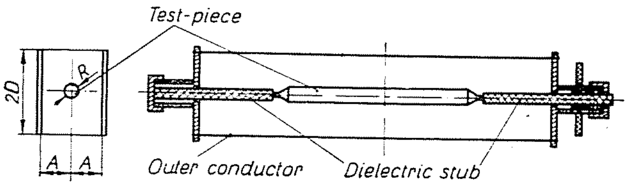
$$\frac{1}{Q_2} = \frac{\frac{\delta_2}{b}}{2 \ln \frac{b}{a}} \tag{7}$$

where a is the radius of the inner conductor,
b the radius of the outer conductor,
δ_1 the skin-depth in the inner conductor,
δ_2 the skin-depth in the outer conductor,
Q_1 the Q factor characteristic of the inner conductor,
Q_2 the Q factor characteristic of the outer conductor.

The maximum Q factor can be achieved if $b/a = 3.6$. As a is much smaller than b, the Q factor is determined mainly by the skin-depth of the inner conductor. The losses due to the outer conductor and the rods were experimentally determined and Q_2 was calculated from this. To secure the minimum possible error, however, the surface of the outer conductor has also been finished with utmost care.

The specific conductance measured on microwaves is given by:

$$\sigma = \frac{1}{\pi f \mu_0} \left[\frac{1}{2a \ln \frac{b}{a}} \cdot \frac{Q_m \cdot Q_e}{Q_e - Q_m} \right]^2 \tag{8}$$



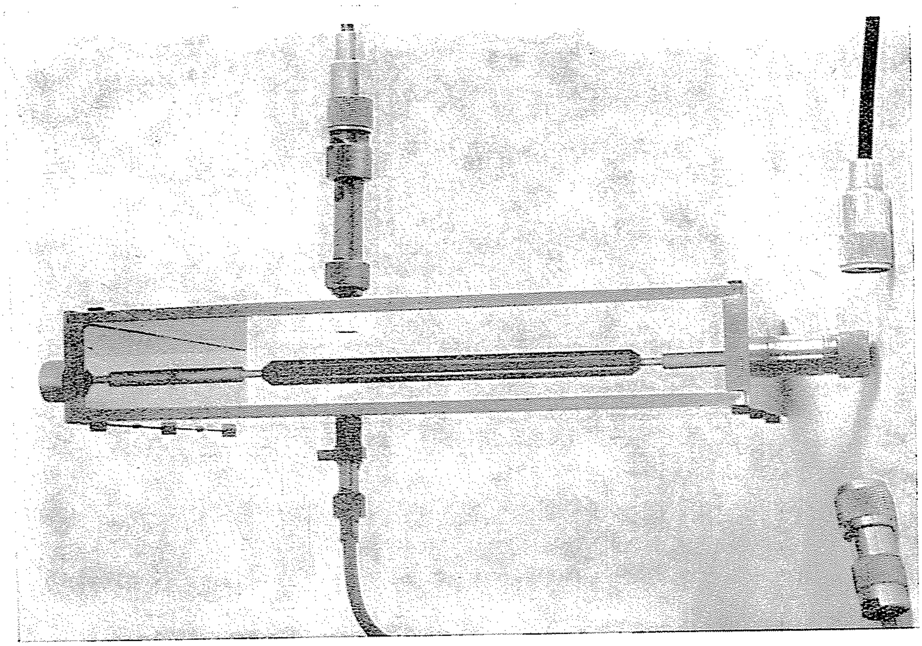


Fig. 4. Special cavity resonator suitable for measuring specific conductance

where f is the frequency,
μ_0 the permeability of the air,
Q_m the Q factor determined by measurement,
Q_e the Q factor characteristic of the equipment, determined during calibration.

Getting the test piece in and out becomes a great deal easier if instead of a cavity made of coaxial line another kind of resonator, consisting of the test piece between two parallel planes is used. This is shown on Fig. 4.

It is well-known that by using the complex function $w = \mathrm{tg}\, z$, the coaxial line can be transformed into a line consisting of a central conductor between two infinite parallel planes. In this transformed line the TEM mode is also possible, so a cavity of the same kind as was used above can also be made of it. If the resonator is made of finite planes instead of infinite ones, then by properly choosing the dimension marked $2D$, the equivalent gap on the coaxial line can be arbitrarily made small. According to calculations, the losses of the infinite planes are the same as the loss in the outer wall of a coaxial cavity, having an outer conductor diameter equal to the distance between the planes. The coupling of the microwave power into the cavity and out to the crystal detector is managed by coupling loops.

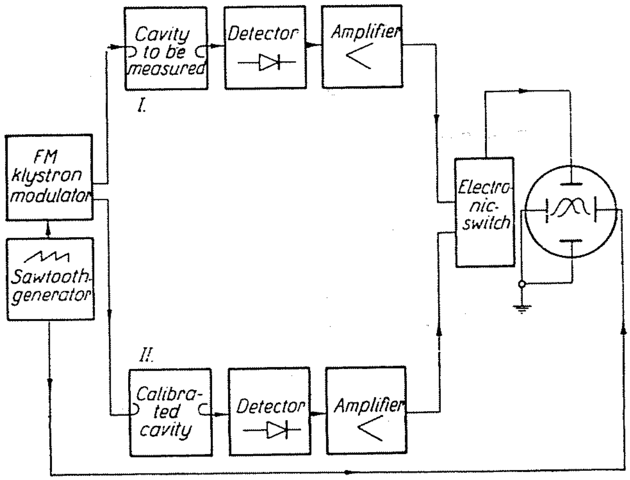
The Q factor of the cavity under test is measured and the conductivity of the test piece is determined by calculation.

$$\sigma = \frac{1}{\pi f \cdot \mu_0} \left[\frac{1}{2 R \ln \frac{4A}{\pi R}} \cdot \frac{Q_m \cdot Q_e}{Q_e - Q_m} \right]^2 \tag{9}$$

where f is the frequency used at the measurement,
μ_0 is the permeability of the air,
A the distance between the planes,
R the radius of the inner conductor,
Q_m the Q factor determined by measurement,
Q_e the Q factor characteristic of the equipment, determined during calibration.

The cavity is compared to a calibrated one, the resonant frequency and Q factor of which can be set equal to those of the cavity under test. The measuring arrangement is shown on Fig. 5.

Both cavity resonators are fed by an oscillator FM modulated by a saw-tooth voltage. The average frequency of the oscillator is equal to the resonant frequency of the cavities. The frequency sweep is greater than the band width between the 3 db points. The a. c. voltage developed on the crystal detectors changes according to the resonance curves of the cavities. These signals are amplified and added together, before an electronic switch alternately lets one after the other onto the scope screen. Owing to the inertness of the eye, the two curves seem to appear simultaneously. By tuning the calibrated cavity to the same frequency of the tested one, the curves might be brought to overlap each other.



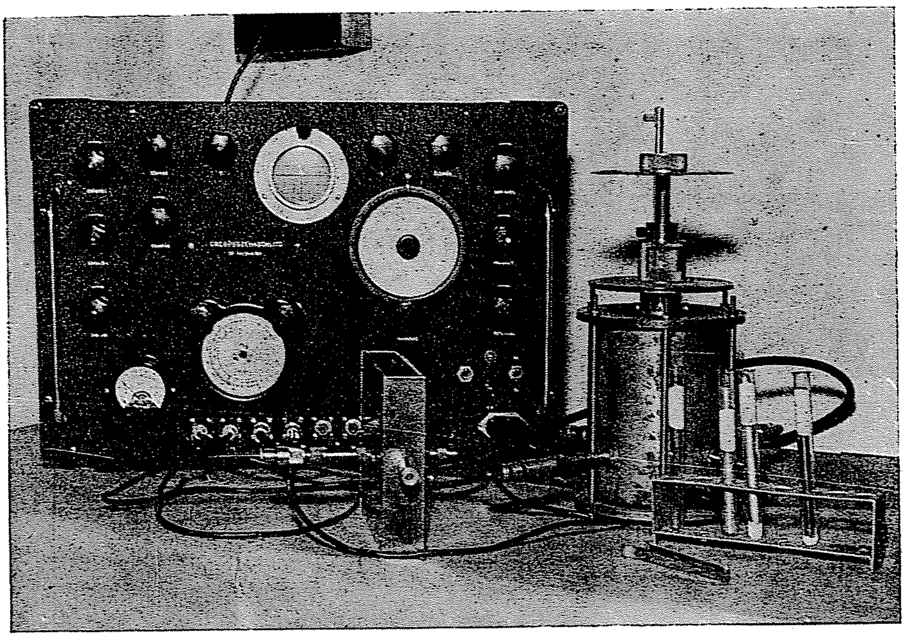
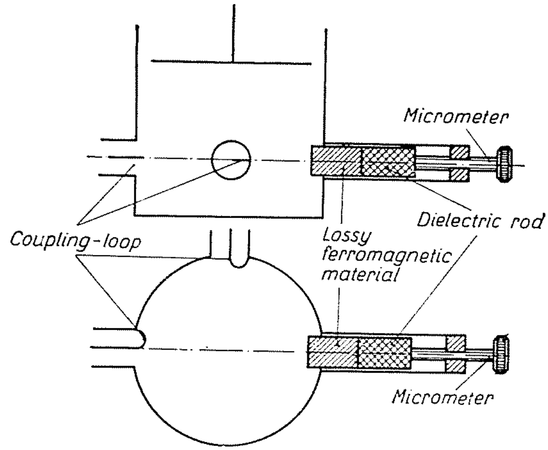


Fig. 5. Comparing the resonant curve of a microwave cavity resonator with that of a calibrated one



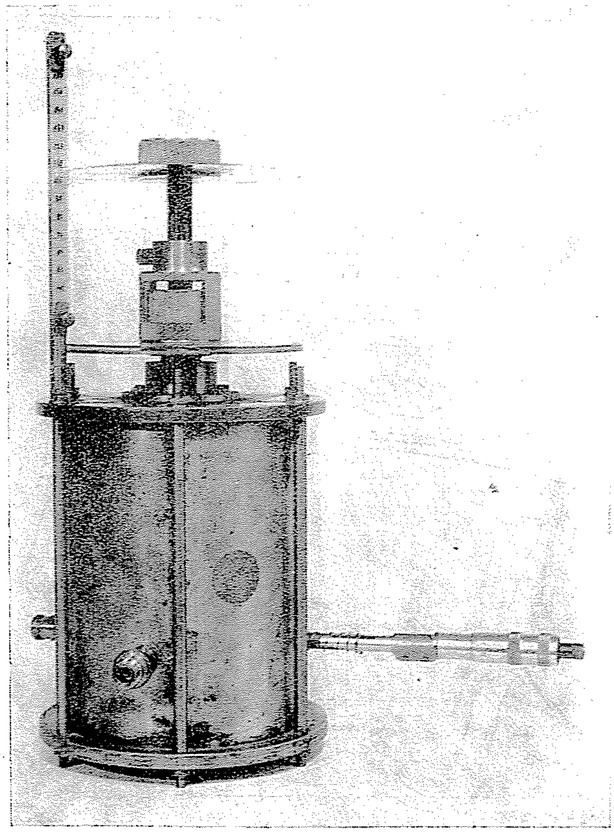
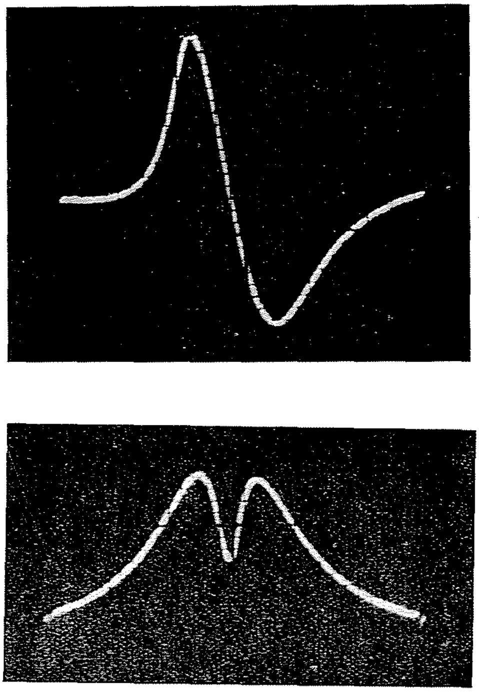


Fig. 6. Cavity resonator with variable Q factor

The calibrated cavity resonator is then so adjusted, that its Q factor takes up the same value as that of the one under test. This condition is fulfilled, when the two resonance curves overlap each other exactly. The Q factors of both cavities are now the same, and this values can be read off from the calibrated cavity resonator.



a

b

Fig. 7. Comparing the resonant curves of cavity-resonators on the scope-screen. *a)* the resonant frequencies of the two cavities are different, *b)* the Q factors of the two cavities are different

The cross-section of the calibrated cavity resonator is shown on Fig. 6. The cavity works in the TE_{011} mode and is tuned by a non-contacting top. The inputs and outputs are managed by coupling loops.

The Q factor of the cavity is made variable by placing ferromagnetic material inside the cavity. The position of this lossy iron-core material is adjusted by a micrometer.

Through proper dimensioning it is possible to change the Q factor without causing a drift of the resonant frequency.

At resonance, namely, the maximum electric and magnetic energies stored in the cavity are the same. If the altering made, when varying the Q factor, causes the same amount of change in both the magnetic and electric fields, the resonant frequency remains the same, as is known from perturbation theory. The adjusting apparatus of the powdered-iron attenuator must not couple out electromagnetic energy from the cavity. The position of the powdered-iron material is therefore changed by way of a polystyrene rod which acts as a cut-off attenuator against the escaping energy. The value of the Q factor plotted against the micrometer divisions is determined by experimental calibration.

The fine frequency adjustment of this cavity is made by moving a polystyrene slug perpendicular to the cavity wall. The frequency drift is either calculated from the perturbation theory or determined experimentally.

The inevitable mistake committed during this method of Q factor measurement depends a great deal on personal judgement and the line width of the scope trace limits the otherwise considerably higher accuracy.

The accuracy of this measurement might be increased a great deal, if instead of comparing the resonance curves, their difference is examined. The voltages corresponding to the resonance curves, resp. are added up in opposite phases and this difference-signal is shown on the scope-screen, as it is given on Fig. 7. The summing up is carried out by the former electronic switch, after the driving signal is turned off, which previously controlled the switching. In this way the same apparatus might be used for both types of measurements.

It is advisable to follow the comparing method only when approximate data are needed, and to use the substraction method only if a high value of accuracy is necessary. To invert the phase of the voltage corresponding to the resonant curve of one of the cavities can be achieved in two different ways:

a) by using an inverse polarity crystal detector;

b) by switching-in a phase inverter stage in the row of the cascaded amplifiers.

The method discussed can be used not only for such tests as are mentioned above, but also for examining new cavities, transmission line joints.

During the course of our tests different technological methods were examined. Most of the experiments dealt with silver layers covered by different protective layers. Besides these, examinations were also carried out regarding natural aluminium, and aluminium alloys covered by different protective layers. The above-discussed method proved very useful when different test pieces were compared with each other, because its relative accuracy is extremely high.

The time reliability of the measurement depends solely on passive elements: on the time stability of the powdered iron core and on the micrometer.

Summary

The microwave surface roughness can be characterized by the ratio of specific resistances measured on microwaves and at very high frequencies, resp.

When measured at very high frequencies, the test piece is placed into a radio frequency coil and the resulting Q factor determines the specific conductance of the test piece. This same test piece can also be placed between dielectric bumpers in a cavity resonator, and this time the Q factor of the cavity will determine the specific conductance of the test piece on microwaves.

Writer designed a method for measuring the Q factors of resonant cavities, which is a quick and yet very accurate measurement, suitable for mass examination too.

The cavity under test is compared with a calibrated one and the differences of the resonant curves of the cavities are examined.

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